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PROCEEDINGS

HIGH STRENGTH ALLOYS FOR SEAWATER FASTENER APPLICATIONS

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ABSTRACT

Slow strain rate tests were conducted on Rene 41, Alloy 925, and Alloy A286. Specimens were evaluated in 3.5% NaCl solution in both freely corroding and cathodically polarized conditions and compared to similar specimens run in air. 5000 hour statically-loaded proving ring tests were also conducted in natural seawater under both freely corroding and cathodically polarized environments to assess the validity of the slow strain rate method in predicting long-term environmental cracking resistance. The proving ring tests were performed on Alloy K-500, Alloy 625 Plus, Alloy 625PH, Ti-6Al-4V ELI, and Beta C titanium. Slow strain rate results indicated good environmental cracking resistance for Alloy A286 in all environments evaluated. Rene 41 exhibited a hydrogen embrittlement susceptibility when polarized to -1000 and -1250 mV vs. SCE. Alloy 925 was susceptible to hydrogen embrittlement at -1250 mV and showed a reduced load bearing capacity in freely corroding, -850, and -1000 mV vs. SCE environments. The proving ring results showed that the slow strain rate method is valid for assessing long-term environmental cracking resistance of fastener alloys.

INTRODUCTION

High strength materials that are utilized in Navy fastener applications require good hydrogen embrittlement/stress corrosion cracking (HE/SCC) resistance as well as galvanic compatibility with the components that they are fastening. Alloy K-500 is currently an approved fastener material per MIL-S-1222 and is typically used in high

strength applications. Alloy K-500 is, however, known to be susceptible to hydrogen embrittlement when cathodically protected (1-3). Due to this environmental cracking susceptibility and to its poor galvanic compatibility with noble metal components, alternate fastener materials are being considered. A research program assessing the HE/SCC resistance of a variety of nickel-base, titanium-base, and iron-base alloys has been ongoing for the past three years. Slow strain rate test (SSRT) results of particular alloys have been previously published (4,5). In this paper, the slow strain rate results of three additional fastener alloys will be presented. Specifically, these alloys are Rene 41, Alloy 925, and Alloy A286. Proving ring test data on nickel- and titanium-base fastener alloys will also be presented to assess the validity of the slow strain rate method in predicting long-term environmental cracking resistance.

MATERIALS

SLOW STRAIN RATE TESTING

The materials evaluated by the slow strain rate test method included Rene 41, Alloy 925, and Alloy A286. The chemical composition and mechanical property data for these alloys is included in Table 1.

PROVING RING TESTING

The fastener alloys utilized in the proving ring tests consisted of Alloy K-500, Alloy 625 Plus, Alloy 625PH, Ti-6Al-4V ELI, and Beta C titanium. The chemical composition and mechanical property certifications by the manufacturer for these alloys was reported previously (5).

EXPERIMENTAL PROCEDURE

SLOW STRAIN RATE TESTING

Slow strain rate tests were performed using notched tensile specimens (5). Specimens were pulled to failure using a displacement rate of 9×10^{-7} in/sec. Each of the fastener alloys were evaluated in conditions of air, freely corroding, and cathodically polarized to -850 mV, -1000 mV, and -1250 mV levels versus a saturated calomel reference electrode (SCE). The freely corroding and cathodic polarization tests were done in 3.5% NaCl solution. Duplicate tests were performed per

condition on each alloy. After testing, each specimen was removed from the test assembly and the fracture surfaces were preserved with plastic spray until SEM examination could be performed.

PROVING RING TESTING

The proving ring tests utilized the same notched tensile specimens as in the slow strain rate tests. Specimens were uniaxially loaded to the 90% yield load level based on slow strain rate air tests performed on each alloy. Static load testing was conducted in ambient temperature, natural seawater with specimens either a) freely corroding or b) polarized to -1000 mV vs. a Ag/AgCl reference electrode. Specimens were tested to failure or were removed from test if no failure had occurred after 5000 hours' exposure. The unfailed specimens were then pulled to failure in air using a 9×10^{-7} in/sec displacement rate, and their fracture surfaces were examined in the SEM.

RESULTS AND DISCUSSION

SLOW STRAIN RATE TESTING

Tables 2-4 document the slow strain rate results for Rene 41, Alloy 925, and Alloy A286. These tables include the time to failure, maximum load attained, and the air/seawater environment ratio for each specimen as well as a summary of the fracture surface appearance after the slow strain rate testing.

The Rene 41 SSRT specimens exhibited predominantly ductile transgranular fracture behavior in air, freely corroding, and -850 mV vs. SCE conditions. For these specimens, approximately 5% of the fracture surfaces contained low ductility areas but no indication of intergranular failure was evident. The SSRT specimens tested at -1000 mV vs. SCE showed a moderate amount of intergranular failure with secondary cracking. The SSRT specimens polarized to -1250 mV vs. SCE displayed fracture surfaces similar to the -1000 mV specimens, but a larger amount of secondary, intergranular cracking was present on the -1250 mV specimens. Although intergranular cracking was found on specimens polarized at both the -1000 and -1250 mV levels, a reduction in the maximum load data versus air was only evident for the -1250 mV specimens. The degree of secondary, intergranular cracking present on the -1000 mV specimens was presumably not enough to show a significant reduction in the maximum load attained as compared to air.

The Alloy 925 material behaved similarly in air, freely corroding,

-850 mV, and -1000 mV environments. The maximum loads attained in all four conditions fell within the same range of values. The appearance of the fracture surfaces after slow strain rate testing showed ductile fracture combined with secondary, intergranular cracking which predominantly occurred at the notch root. This ductile intergranular failure mode indicates a reduced load bearing capacity for this alloy as compared to a material that fractures in a ductile transgranular mode.

The Alloy 925 SSRT specimens that were cathodically polarized to -1250 mV exhibited evidence of hydrogen embrittlement. Both specimens contained a moderate amount of secondary intergranular cracking that was concentrated at the notch root. The maximum load values were also reduced in comparison to the air values.

The Alloy A286 SSRT specimens exhibited good environmental cracking resistance in all of the environments evaluated. The SSRT data for this alloy indicated a slight reduction in maximum load for the cathodically polarized specimens as compared to air; however, examination of the fracture surfaces did not suggest a hydrogen-assisted cracking mechanism. The fracture surface appearance of all of the Alloy A286 specimens showed ductile transgranular behavior over 95% of the surfaces. The remaining 5% of the fracture surfaces contained low ductility areas with porosity present around precipitates. Energy dispersive x-ray analysis of these areas showed the precipitates to be titanium-rich.

PROVING RING TESTING

A comparison of the proving ring and slow strain rate test results for nickel- and titanium-base fastener alloys is found in Tables 5-6. The SSRT data in these tables was reported previously (5). With the exception of the Alloy 625PH proving ring specimens that were cathodically polarized to -1000 mV, all of the proving ring specimens were in test for 5000 hours without failure and then were pulled to failure in air at a displacement rate of 9×10^{-7} in/sec. The cathodically polarized Alloy 625PH proving ring specimens failed after <48 and <120 hours, respectively.

The nickel- and titanium-base alloys exhibited a ductile fracture mode for both the proving ring and slow strain rate specimens tested in freely corroding conditions. Although some cracking was present on the titanium alloy specimens, the cracking was not intergranular and did not indicate an environmental cracking susceptibility. The three nickel-base alloys tested at -1000 mV all displayed a hydrogen embrittlement susceptibility in both the proving ring and slow strain rate tests.

Moderate to extensive secondary intergranular cracking was found on all cathodically polarized nickel-base alloy specimens except Alloy 625 Plus SSRT specimens. The Alloy 625 Plus specimens exhibited isolated areas of intergranular fracture concentrated at the notch root. The two titanium-base alloys exhibited a ductile failure mechanism under -1000 mV conditions in both the proving ring and slow strain rate tests. The slight to moderate degree of cracking evident on the titanium specimens was not intergranular and showed no indication of environmental cracking.

The maximum loads attained on the nickel-and titanium-base alloys did show some variability between the slow strain rate and proving ring tests. In the freely corroding environment, the maximum loads for the nickel-base proving ring specimens were either similar or lower than the slow strain rate specimens. In the cathodically polarized condition, the Alloy K-500 and Alloy 625 Plus proving ring specimens were consistently lower than the slow strain rate specimens. These reduced loads were presumably due to more extensive intergranular cracking present on the proving ring specimens, which resulted in a reduction in the maximum load attained. The Alloy 625PH material exhibited similar maximum loads for both the slow strain rate and proving ring tests, corresponding to a similar degree of intergranular cracking present on these specimens. For the Ti-6Al-4V ELI and Beta C alloys, the maximum loads attained in both freely corroding and cathodically polarized conditions were either similar or lower in the proving ring tests as compared to the slow strain rate tests.

In summary, there was good correlation between the proving ring and SSRT results. SSRT results for these high strength fastener alloys have typically shown variability in the maximum loads reported and thus, the primary criteria for predicting environmental cracking resistance has been the fracture surface appearance (5). Based on the fracture surface evaluation of the nickel- and titanium-base alloys, the resistance or susceptibility to environmental cracking in the freely corroding and cathodically polarized environments was consistent between the slow strain rate and proving ring tests. Thus, the accelerated slow strain rate test appears to be valid for predicting long-term environmental cracking resistance of high strength fastener alloys.

CONCLUSIONS

o Rene 41 has good environmental cracking resistance in freely

corroding and -850 mV vs. SCE conditions. This nickel-base alloy is susceptible to hydrogen embrittlement when polarized to -1000 and -1250 mV vs. SCE.

o Alloy 925 exhibited a ductile intergranular fracture mode in air, freely corroding, -850, and -1000 mV vs. SCE conditions; this intergranular fracture behavior indicates a reduced load bearing capacity for this alloy as compared to an alloy that fractures in a ductile transgranular mode. Alloy 925 is susceptible to hydrogen embrittlement when cathodically polarized to -1250 mV vs. SCE.

o Alloy A286 displayed good environmental cracking resistance in air, freely corroding, and cathodically polarized environments.

o A comparison of short-term slow strain rate and long-term proving ring tests indicated that the slow strain rate method is valid for assessing the long-term environmental cracking resistance of high strength fastener alloys.

REFERENCES

1. Efird, K.D., "Failure of Monel Ni-Cu-Al Alloy K-500 Bolts in Seawater," Materials Performance, Vol. 24, No. 4, 1985.

2. Faller, K. and W.A. Edmonds, "The Incentives for Titanium Alloy Fasteners in the Navy/Marine Environment," 1991 Ship Maintenance in the 21st Century Symposium, American Society of Naval Engineers, Virginia Beach, VA, 1991.

3. Joosten, M.W., and L.H. Wolfe, "Failures of Nickel-Copper Bolts in Subsea Applications," 19th Annual Offshore Technology Conference, Paper No. 5553, Houston, TX, 1987.

4. Aylor, D.M., "A Hydrogen Embrittlement Evaluation of High Strength, Non-Ferrous Materials for Fastener Application," Proceedings of the Tri-Service Conference on Corrosion, Plymouth, MA, 1992.

5. Aylor, D.M., "An Environmental Cracking Evaluation of Fastener Materials for Seawater Applications," Corrosion '94, National Association of Corrosion Engineers, Paper No. 484, Baltimore, MD, 1994.

TABLE 1 – Chemical composition and mechanical property data for fastener alloys

Manufacturers' Certification

Material	Composition	Condition	UTS (ksi)	0.2% YS (ksi)	% Reduction in Area	% Elongation
Rene 41 (GXI)	Ni–19Cr–10Mo–11Co–3Ti–3Fe–1.5Al	1975F 1 Hr/WQ, 1400F 16 Hrs/Air Cool	203.6	141.5	37.0	28.8
Alloy 925 (GYP)	Ni–27Fe–21Cr–3Mo–2Ti–2Cu	1850F/WQ, 1365F 8 Hrs, Furnace Cool at 50 deg/hr to 1150F 8 Hrs/Air Cool	168.3	110.5	45.0	27.0
Alloy A286 (GYO)	Fe–25Ni–14Cr–2Ti–1Mo	1800F 1 Hr/Oil Quench, 1325F 16 Hrs/Air Cool	152.6	143.0	48.9	11.2

Specification Requirements

Material	Specification	UTS ksi, min.	0.2% YS ksi, min.	% Reduction in Area, min	% Elongation, min.
Rene 41	AMS 5712	170	130	10	8
Alloy A286	ASTM A453	130	85	18	15

TABLE 2 – Rene 41 slow strain rate test results

Test Environment	Time to Failure (hrs)	Maximum Load (lbs)	%Air Average	Fracture Surface Appearance After Slow Strain Rate Testing
Air	15.3	2305	—	95% Ductile transgranular; 5% low ductility areas but no IG cracking.
Air	16.3	2364	—	95% Ductile transgranular; 5% low ductility areas but no IG cracking.
Freely Corroding	17.1	2281	97.7	Unable to assess fracture surface due to tenacious lacquer coating sprayed on surface after slow strain rate testing.
Freely Corroding	14.0	2297	98.4	Ductile transgranular with low ductility areas but no IG cracking.
–850 mV	19.1	2212	94.8	95% Ductile transgranular; 5% low ductility areas but no IG cracking.
–850 mV	13.6	2302	98.6	95% Ductile transgranular; 5% low ductility areas but no IG cracking.
–1000 mV	13.9	2271	97.3	IG Cracking – Moderate
–1000 mV	15.8	2363	101.2	IG Cracking – Moderate
–1250 mV	14.5	2052	87.9	IG Cracking – Extensive
–1250 mV	18.1	2156	92.4	IG Cracking – Extensive

TABLE 3—Alloy 925 slow strain rate test results

Test Environment	Time to Failure (hrs)	Maximum Load (lbs)	% Air Average	Fracture Surface Appearance After Slow Strain Rate Testing
Air	15.7	2510	—	Ductile Intergranular
Air	14.7	2545	—	Ductile Intergranular
Freely Corroding	17.5	2554	101.0	Ductile Intergranular
Freely Corroding	15.2	2572	101.8	Ductile Intergranular
–850 mV	15.4	2508	99.2	Ductile Intergranular
–850 mV	15.8	2516	99.5	Ductile Intergranular
–1000 mV	15.7	2447	96.8	Ductile Intergranular
–1000 mV	15.8	2524	99.9	Ductile Intergranular
–1250 mV	15.4	2349	92.9	IG Cracking–Moderate
–1250 mV	14.8	2312	91.5	IG Cracking–Moderate

TABLE 4 – Alloy A286 slow strain rate test results

Test Environment	Time to Failure (hrs)	Maximum Load (lbs)	% Air Average	Fracture Surface Appearance After Slow Strain Rate Testing
Air	13.5	2460	—	95% Ductile Transgranular; 5% Low ductility areas but no IG cracking
Air	14.7	2435	—	95% Ductile Transgranular; 5% Low ductility areas but no IG cracking
Freely Corroding	15.9	2490	101.7	95% Ductile Transgranular; 5% Low ductility areas but no IG cracking
Freely Corroding	15.1	2484	101.5	95% Ductile Transgranular; 5% Low ductility areas but no IG cracking
–850 mV	14.7	2345	95.8	95% Ductile Transgranular; 5% Low ductility areas but no IG cracking
–850 mV	15.6	2324	95.0	95% Ductile Transgranular; 5% Low ductility areas but no IG cracking
–1000 mV	15.3	2300	94.0	95% Ductile Transgranular; 5% Low ductility areas but no IG cracking
–1000 mV	15.3	2333	95.3	95% Ductile Transgranular; 5% Low ductility areas but no IG cracking
–1250 mV	15.5	2358	96.3	95% Ductile Transgranular; 5% Low ductility areas but no IG cracking
–1250 mV	15.8	2374	97.0	95% Ductile Transgranular; 5% Low ductility areas but no IG cracking

TABLE 5–Proving ring and slow strain rate test results for nickel-base alloys

Material	Test Method	Environment	Maximum Load (lbs)	Maximum Stress (psi)	Fracture Surface Appearance After Slow Strain Rate Testing
Alloy K-500	Proving Ring	Freely Corroding	2005	163906	Ductile Transgranular
		Freely Corroding	2718	222193	Ductile Transgranular
		−1000 mV	1615	132236	IG Cracking – Extensive
		−1000 mV	1623	130577	IG Cracking – Extensive
	Slow Strain Rate	Freely Corroding	2572	209585	IG Cracking – Trace
		Freely Corroding	2528	205671	Ductile Transgranular
		−1000 mV	2320	191803	IG Cracking – Moderate
		−1000 mV	2152	175080	IG Cracking – Moderate
Alloy 625 Plus	Proving Ring	Freely Corroding	3570	290445	Ductile Transgranular
		Freely Corroding	3344	272058	Ductile Transgranular
		−1000 mV	2386	192576	IG Cracking – Moderate
		−1000 mV	2304	188048	IG Cracking – Moderate
	Slow Strain Rate	Freely Corroding	3448	285518	Ductile Transgranular
		Freely Corroding	3438	281503	Ductile Transgranular
		−1000 mV	2912	234656	IG Fracture – Slight
		−1000 mV	2888	231983	IG Fracture – Slight
Alloy 625PH	Proving Ring	Freely Corroding	2635	214034	Ductile Transgranular
		−1000 mV	3092*	251155	IG Cracking – Moderate
		−1000 mV	3092*	251155	IG Cracking – Moderate
	Slow Strain Rate	Freely Corroding	3724	281429	Ductile Transgranular
		Freely Corroding	3274	266789	Ductile Transgranular
		−1000 mV	3088	249234	IG Cracking – Moderate
		−1000 mV	3035	245347	IG Cracking – Moderate

*Specimens failed in proving rings <48 and <120 hours, respectively after exposure in natural seawater and cathodically polarized to −1000 mV vs. Ag/AgCl. All other proving ring specimens were unfailed after 5000 hours exposure and were pulled to failure in air.

TABLE 6—Proving ring and slow strain rate test results for .anium–base alloys

Material	Test Method	Environment	Maximum Load (lbs)	Maximum Stress (psi)	Fracture Surface Appearance After Slow Strain Rate Testing
Ti-6Al-4V ELI	Proving Ring	Freely Corroding	2686	218525	Ductile Transgranular–Slight Cracking
		Freely Corroding	2112	171826	Ductile Transgranular–Slight Cracking
		–1000 mV	2106	171338	Ductile Transgranular–Slight Cracking
		–1000 mV	2088	170418	Ductile Transgranular–Slight Cracking
	Slow Strain Rate	Freely Corroding	2542	207473	Ductile Transgranular
		Freely Corroding	2774	225324	Ductile Transgranular
		–1000 mV	2840	234038	Ductile Transgranular
		–1000 mV	2780	229093	Ductile Transgranular
Beta C	Proving Ring	Freely Corroding	1996	162649	Ductile, Faceted Areas–Moderate Cracking
		Freely Corroding	2610	212682	Ductile, Faceted Areas–Moderate Cracking
		–1000 mV	1955	159308	Ductile, Faceted Areas–Moderate Cracking
		–1000 mV	2479	202655	Ductile, Faceted Areas–Moderate Cracking
	Slow Strain Rate	Freely Corroding	2697	216297	Ductile, Faceted Areas–Slight cracking
		Freely Corroding	2516	203392	Ductile, Faceted Areas–Slight cracking
		–1000 mV	2580	206913	Ductile, Faceted Areas–Slight cracking
		–1000 mV	2700	216537	Ductile, Faceted Areas–Slight cracking